Geology of the Shark Bay area, Western Australia.

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Abstract

Shark Bay is a shallow embayment bounded by peninsulas and islands, which are thought to be localized by subsurface Tertiary anticlines. Rocks exposed in the area consist of Cretaceous chalk, Tertiary sandstone and limestone, Pleistocene eolian limestone, eolian sandstone, marine limestone, and evaporites, and Holocene sands, beach-ridge deposits, and stromatolites.

The Pleistocene eolian limestone (Tamala Limestone) accumulated as enormous dunes on the western shoreline of the area during glacial periods of the Pleistocene, when the area was subject to extremely strong southerly winds. The linear development of the unit along the Zuytdorp Cliffs may be defined by a Quaternary fault.

The Hamelin Coquina is a beach-ridge deposit laid down around the hypersaline waters of Hamelin Pool and Lharidon Bight, and composed almost entirely of shells of the small bivalve *Fragum erugatum*, which thrives in the hypersaline conditions. Hamelin Pool became a hypersaline barred basin about 4,200 years ago, when the Faure Sill developed across its entrance, restricting inflow of open-marine waters from the rest of Shark Bay. Growth of stromatolites on the shallow sublittoral platform and intertidal zone of Hamelin Pool may have begun at about that time.

Hamelin Pool contains the most abundant and diverse stromatolites known in the world's oceans. They are believed to occur there because the hypersaline conditions have severely reduced or eliminated elements of the marine biota that would otherwise consume the stromatolite-building microorganisms or compete with them for ecological niches.

The three main types of benthic microbial communities that construct stromatolites at Hamelin Pool are termed pustular, smooth, and colloform mats. They are composed of distinct communities of cyanobacteria ("blue-green algae"), and microalgae. Pustular-mat stromatolites are confined to intertidal environments, smooth-mat stromatolites to lower intertidal and shallow subtidal environments, and colloform-mat stromatolites to subtidal environments (extending to depths of up to 4 m). The external morphology of the stromatolites is largely controlled by environmental factors, whereas biological factors are mainly responsible for differences in their internal fabrics.

The Hamelin Pool stromatolites are extremely slow growing, with measured growth rates of less than 0.5 mm per year, and they are consequently very susceptible to long-term damage by human activities. Many individual stromatolites are believed to be hundreds or even thousands of years old.

Résumé

Shark Bay est une baie peu profonde bordée de péninsules et d'îles que l'on pense être localisées audessus d'anticlinaux tertiaires en subsurface. Les roches qui affleurent dans la région consistent en craie du Crétacé, grès et calcaires du Tertiaire, calcaires et grès éoliens, calcaires marins et évaporites du Pléistocène, ainsi qu'en sables, dépots de levée de plage et stromatolites de l'Holocène.

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Les calcaires éoliens pléistocènes (Tamala Limestone) se sont déposés en vastes dunes sur la côte occidentale de la région durant les périodes glacières du Pléistocène, lorsque la région était sous l'influence de vents méridionaux extrêmement forts. Le développement linéaire de cette formation le long de Zuytdorp Cliffs peut être attribuî à faille quaternaire.

Le Hamelin Coquina est une lumachelle déposée autour des eaux hypersalines de Hamelin Pool et de Lharidon Bight, et elle est composée presque entièrement de petits bivalves *Fragum erugatum,* qui abondent dans les conditions hypersalines. Il y a environ 4,200 ans, Hamelin Pool est devenu un bassin hypersalin suite à l'obstruction de son entrée par une barre sableuse, lorsque le Faure Sill se développa, restreignant les échanges d'eaux marines avec le reste de Shark Bay. Le développement de stromatolites sur la plateforme sublittorale peu profonde et dans la zone intertidale de Hamelin Pool a pu commencer à cette époque.

Les stromatolites de Hamelin Pool représentent les plus abondantes variétés dans les océans actuels. Leur développement peut être attribué aux conditions hypersalines qui auraient fortement réduit ou éliminé une partie du biotope marin qui qurait autrement détruit les micro-organismes constructeurs de stromatolites ou aurait été en compétition pour la niche écologique.

Les communautés microbiennes benthiques qui construisent les stromatolites de Hamelin Pool sont subdivisées en trois principaux types: pustuleux, lisses et botryoïdes. Elles sont composées de communautés distinctes de cyanobactéries ("algues bleues") et d'algues microscopiques. Les stromatolites pustuleux sont confinés aux milieux intertidaux, les stromatolites lisses aux milieux intertidaux inférieurs et néritiques peu profonds, et les stromatolites botryoïdes aux milieux infratidaux (s'étendant à des profondeurs allant jusqu' à 4 m). La morphologie externe des stromatolites est largement controlée par les facteurs écologiques, tandis que les facteurs biologiques sont principalement responsables des différences dans leurs structures et textures internes.

Les stromatolites de Hamelin Pool ont une croissance extrêmement lente, avec des taux de croissance inférieurs à 0.5 mm par an, et ils sont par conséquent vulnérables aux dommages causés à long terme par les activités humaines. On suppose que de nombreux stromatolites individuels sont âgés de centaines ou même de milliers d'années.

Introduction

Shark Bay is a shallow area of sea in the southern Carnarvon Basin, bounded to the west by Dirk Hartog, Dorre, and Bernier Islands, and Edel Land Peninsula, and divided into two arms by Peron Peninsula (Figure 1).

The Shark Bay area was almost unknown geologically until the mid 1950s, when West Australian Petroleum Pty Ltd conducted the first reconnaissance geological survey of the area (Johnstone and Playford 1955, Playford and Chase 1955), and drilled a series of holes on Dirk Hartog Island. Since then there has been a considerable amount of mapping and other research carried out in the area by geologists of the University of Western Australia, Geological Survey of Western Australia, and Baas Becking Geobiological Laboratory.

The Geology Department, University of Western Australia, commenced detailed studies of Holocene sedimentation in the Shark Bay area in the late 1950s (Logan 1959, 1961), and B. W. Logan and his co-workers have since published two comprehensive monographs on this work (Logan *et al.* 1970, Logan, Read, *et al.* 1974). The Geological Survey of Western Australia has studied the stromatolites of Hamelin Pool since 1968, and mapped the area during the

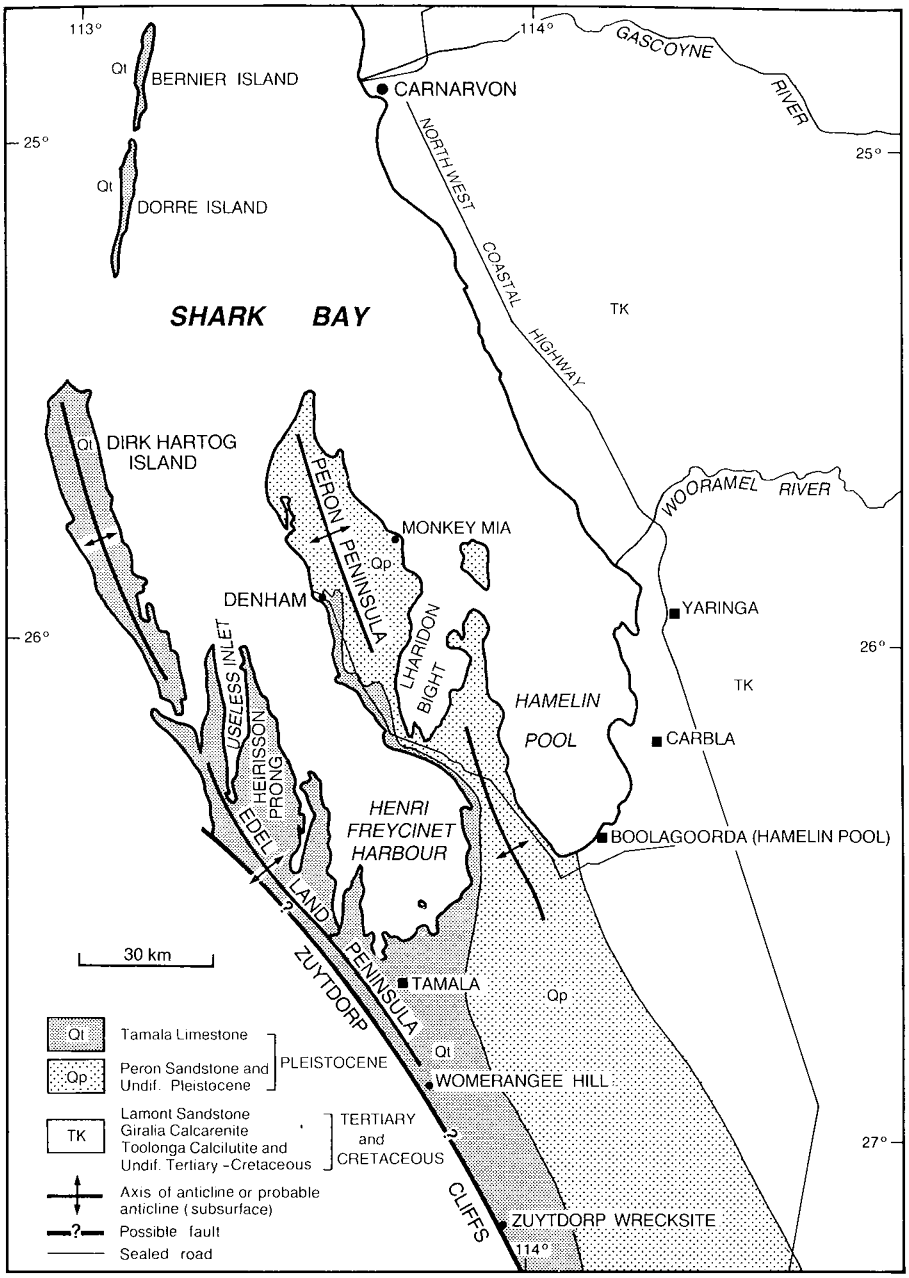

Figure 1. Generalized geological map of the Shark Bay area.

1970s (Playford and Cockbain 1976; Playford 1980a, 1980b, Butcher *et al.* 1984; Denman *et al.*, 1985; van de Graff *et al.*, 1983; Hocking *et al.* 1987). The Baas Becking Geobiological Laboratory carried out detailed biological, sedimentological, and meteorological studies at Hamelin Pool during the late 1970s and 1980s (Bauld *et al.* 1979; Bauld 1984; Burne and James 1986; Walter and Bauld 1986; Skyring and Bauld in press), and further details of biological aspects of this work are being documented for publication.

Geomorphology

The peninsulas and islands which confine and divide Shark Bay consist of Pleistocene and Holocene dune deposits, which are thought to have accumulated on anticlinal ridges of Tertiary limestone (Figure 1). The hypothesis that the gross modern morphology is controlled by underlying folds was first proposed by Playford and Chase (1955), and was confirmed in the case of Dirk Hartog Island by a program of structure drilling for petroleum exploration (Butcher *et al.* 1984).

North-south promontories on the eastern side of Edel Land Peninsula (such as Bellefin Prong), and the associated inlets (such as Useless Inlet) are defined

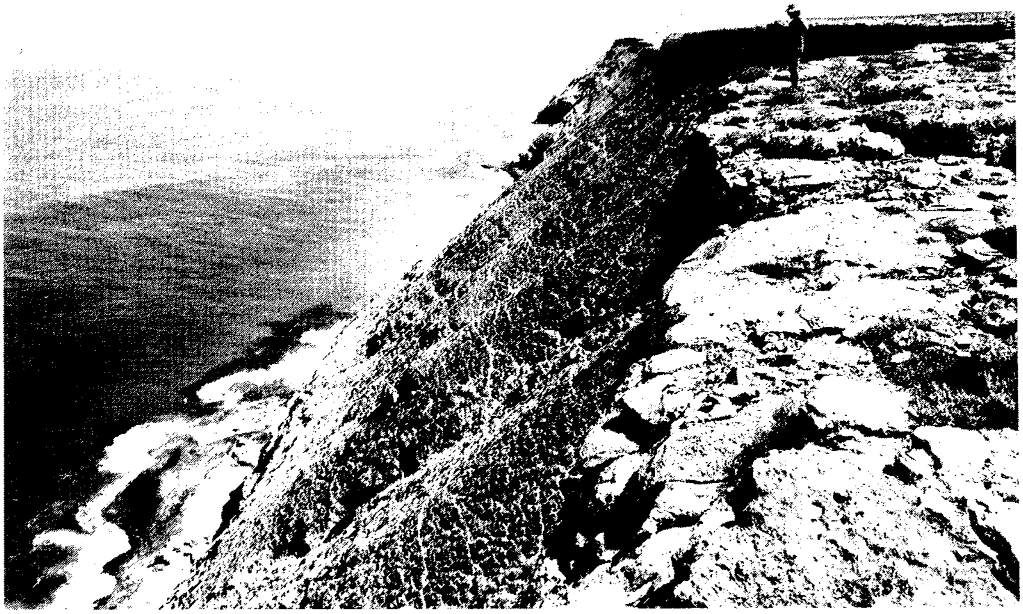

Figure 2. The Zuytdorp Cliffs, adjoining Womerangee Hill. The type section of the Tamala Limestone is exposed at this locality, which marks the highest point along the cliffs (270 m above sealevel).

by major longitudinal dune ridges and interdune valleys in the Pleistocene Tamala Limestone. These formed parallel to the strong prevailing southerly winds.

Similar north-south longitudinal dune ridges, in red sand over Peron Sandstone, occur on Peron Peninsula, and are also believed to be of Pleistocene age. The longitudinal dunes are connected by subordinate transverse dunes, and the interdunal depressions are occupied by playa lakes, known by their Aboriginal name as birridas. These are also believed to have originated during the Pleistocene.

The most striking geomorphological feature of the Shark Bay area, and one of the most remarkable features of the Western Australian coast, is the Zuytdorp Cliffs. These form a straight line of sheer cliffs, up to 270 m high, marking the western side of Edel Land Peninsula, and extending south for some 200 km to Kalbarri (Figure 2). They are named after the Dutch ship *Zuytdorp*, which was wrecked at the foot of the cliffs 60 km south of Shark Bay in 1712 (Playford

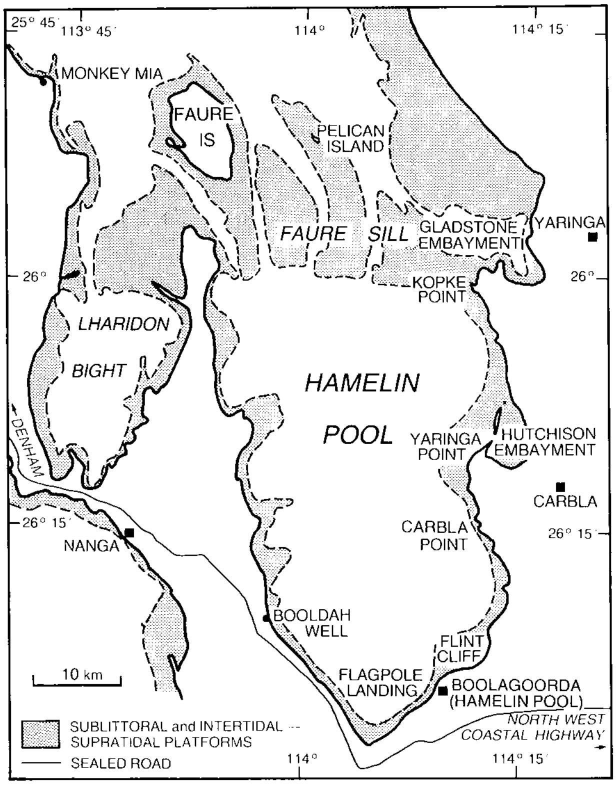

Figure 3. Map of the Hamelin Pool area showing sublittoral and intertidal-supratidal platforms and the Faure Sill, which restricts circulation between Hamelin Pool and the open ocean.

1960). The cliffs are composed of Pleistocene dune limestone (Tamala Limestone) and may be controlled by a fault, although it is not known whether this has moved during the Quaternary (Megallaa 1980, Butcher *et al.* 1984). Similar cliffs mark the west coast of Dirk Hartog Island.

Hamelin Pool forms the southeastern arm of Shark Bay. It is a hypersaline embayment, partially barred from the rest of the bay by a sand and seagrass bank, the Faure Sill (Figure 3). The water is hypersaline, with salinities up to nearly double that of the open sea, because tidal exchange is severely restricted by the shallow bank, rainfall is low, and evaporation is high. The hypersaline conditions are primarily responsible for the remarkable stromatolites and shell deposits (Hamelin Coquina) that occur around the margins of Hamelin Pool.

The most important control on the various types of stromatolites found in Hamelin Pool is the tidal range, but previous investigations have been made without the benefit of accurate tide data. As a result, the Geological Survey arranged for a tide gauge to be installed by the Department of Marine and Harbours (through Mr D.F. Wallace) at Flagpole Landing, Hamelin Pool, for

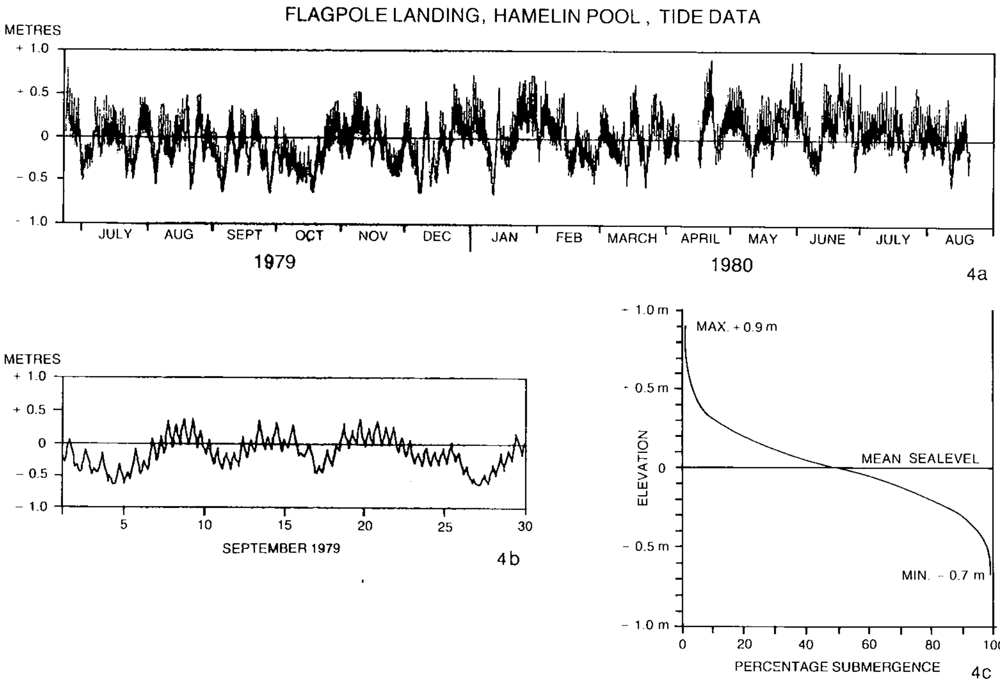

Figure 4. Tide data for Hamelin Pool obtained at Flagpole Landing in 1979-80 by the Department of Marine and Harbours. 4a. - Tide records for the period June 1979 to August 1980. 4b - Tide records for September 1979. 4c - Cumulative frequency curve for water levels at Flagpole Landing over a period of 416 days in 1979/80.

15 months from June 1979 to August 1980 (minus a 6-day gap in April 1980). Water levels were recorded every 15 minutes, giving some 40,000 pieces of information, which are synthesized in Figure 4a.

The main changes in water level at Hamelin Pool are linked to the weather. The approach of a low-pressure system causes the water level to rise, while a high-pressure system causes it to fall. In general the highest levels occur during winter, the lowest in summer. No cyclone passed through the area when the records were being obtained, but my own observations showed that Cyclone Hazel caused the water level at Flapole Landing to rise about 4 m above mean sealevel on 13 March 1979.

The tides at Hamelin Pool are classed as mixed semi-diurnal and diurnal, but are predominantly semi-diurnal (see record for September 1979, Figure 4b). The average daily tidal range is about 0.4 m (D.F. Wallace, pers. comm. 1981). The cumulative frequency curve (Figure 4c) shows the percentage submergence above and below mean sealevel for the period that the gauge was installed. The total extent of water-level change during the 416 days of observation was 1.6 m. A point 0.9 m above mean sealevel was submerged on only one day, one at 0.2 m above mean sealevel was submerged on 83 days (20% of the time), and so on down to a point of 0.7 m below mean sealevel, which remained submerged for 415 of the 416 days.

General geology

The surface geology of the Shark Bay area west of Hamelin Pool consists of Pleistocene and Holocene limestone and sandstone, largely covered by superficial sand (Figure 1). East of Hamelin Pool the area is largely covered by calcretised Cretaceous chalk, with some overlying Tertiary sandstone and calcarenite. Drilling has shown that the Shark Bay area is underlain by a thick sequence of Tertiary limestone, Cretaceous chalk, sandstone, shale, and Silurian sandstone, limestone, dolomite, and evaporites. Details of this subsurface sequence are outlined by Hocking *et al.* (1987); the surface geology only will be further discussed in this paper.

Cretaceous

The *Toolonga Calcilutite*, of Late Cretaceous age, is the oldest unit exposed in the area. It outcrops discontinuously along the east side of Hamelin Pool from Flint Cliff to Yaringa Station. The unit consists of white chalk and greenish-white lime mudstone, usually altered to calcrete at the surface, and often containing abundant chert nodules.

Tertiary

The Eocene *Giralia Calcarenite* consists of greenish-grey calcarenite exposed at a few localities east of Hamelin Pool, overlying Toolonga Calcilutite. The Miocene *Lamont Sandstone* consists of silicified sandstone exposed in rocky headlands, such as Carbla Point, and a few other localities near the east shore of Hamelin Pool, overlying Toolonga Calcilutite.

Pleistocene

The *Peron Sandstone* is a unit of red eolian sandstone, which is primarily exposed on Peron Peninsula. It is overlain by Tamala Limestone, and possibly interfingers with the lower part of that formation. The Peron Sandstone accumulated as a series of interlocking longitudinal and transverse dunes (Hocking *et al.* 1987).

The *Tamala Limestone* consists of a succession of eolian limestones, most of which accumulated during glacial periods of the Pleistocene, when sealevel was much lower than it is today. The unit is mainly developed on the Edel Land Peninsula, bounded to the west by the Zuytdorp Cliffs, which may be the physiographic expression of a Quaternary fault. The type section is at the highest point of these cliffs, adjoining Womerangee Hill (Figure 2), where its measured thickness is 270 m (Johnstone and Playford 1955). The total thickness of the Tamala Limestone in this area (extending below sealevel) probably exceeds 300 m, which is the thickest development known throughout the extent of the formation, from Shark Bay to the south coast of Western Australia. The prevailing southerly winds that formed the enormous dunes of the Tamala Limestone in the Shark Bay area during the low sealevel stands of the Pleistocene are thought to have been the strongest along the Western Australian coast at that time. They were considerably stronger than the prevailing southerlies in the area today, which are still the most powerful prevailing winds in Western Australia.

The *Dampier Limestone* is the oldest marine Pleistocene unit in the Shark Bay area, probably dating from the penultimate interglacial period, although it has yet to be accurately dated. It consists of shelly limestone laid down under waters of normal marine salinity. The *Carbla Oolite Member* is recognized within the Dampier Limestone on the shores of Hamelin Pool.

The *Depuch Formation* is a unit of calcarenite and calcirudite which occurs in narrow strips along the east side of the Edel Land Peninsula. It is believed to have formed by the erosion and reworking of older Pleistocene units.

The *Bibra Limestone* consists largely of beach-ridge deposits, with some tidal-flat and coralline deposits, exposed along parts of the Shark Bay coastline. The unit contains an open-marine fauna, and is believed to have been deposited during the last interglacial period (ca. 120,000 years ago). Hamelin Pool was not hypersaline at that time, as shown by the open-marine fauna of the Bibra Limestone around its shores.

Evaporite deposits occur in birridas between Pleistocene dune ridges. They consist largely of gypsum, and have been mined at places on the Edel Land Peninsula. The deposits have not been accurately dated, but are believed to be Pleistocene. They are overlapped by Holocene dune ridges (Hamelin Coquina) on the east side of Hamelin Pool and have been inundated by the sea near the northwest end of Peron Peninsula.

An interesting consequence of the inundation of Pleistocene evaporites is found on the west side of Hamelin Pool, north of Booldah Well. At this locality there are numerous circular ponds on the supratidal flats, up to about 20 m in diameter and 5 m deep, which are believed to be due to collapse following the subsurface solution of gypsum in a buried birrida deposit (presumably dissolved by groundwater flowing out from the land below the surface). The ponds ("blue holes") are filled with brine, and the water is replenished periodically following very high tides. The incoming water, although itself hypersaline, is less salty than the brine already in the ponds, and consequently it spreads out as a fresher surface layer, causing the ponds to become meromictic ("solar ponds").

The temperature of the brine below the hermocline rises by as much as 20°C. When the ponds are meromictic they are a bright blue colour - hence the name "blue holes". Stratification of the water is lost with time as the surface layer becomes more salty through evaporation, or mixing occurs as a result of wind action, and the ponds then become greenish in colour.

Holocene

Detailed information on aspects of Holocene sedimentation in the Shark Bay area is given in the monographs by Logan *et al.* (1970) and Logan, Read *et al.* (1974). Superficial Holocene sand, calcrete, and beach deposits occur extensively throughout the area, but the most interesting Holocene units are found around the shores of Hamelin Pool. These are the famous stromatolites and Hamelin Coquina, which are discussed in more detail than other features of Shark Bay geology in this paper.

Many elements of the open-marine fauna and flora found elsewhere in Shark Bay are unable to survive in Hamelin Pool because of its hypersalinity. On the other hand, some forms that can adapt to the high salinity are able to thrive there, due in part to the reduced abundance and diversity of competitors and predatory and grazing animals. The most conspicuous example of such a species is the small bivalve *Fragum erugatum*, which is by far the dominant mollusc in Hamelin Pool. This species also flourishes in Lharidon Bight, which is similarly hypersaline, but it is not so abundant elsewhere in Shark Bay. Its dead shells have accumulated in vast numbers on the shores of Hamelin Pool and Lharidon Bight, to form the Hamelin Coquina (Figure 5).

The *Hamelin Coquina* consists of a succession of beach ridges, in a belt up to 1 km wide and 4 m thick, around the shores of Hamelin Pool and Lharidon Bight. The beach ridges are composed almost entirely of single shells, uniform in size, of *Fragum erugatum*. The beach ridges consist of loose coquina along the modern shoreline, but become progressively more cemented to coquinite in the older beach ridges away from the coast. The loose shells have been excavated, for a variety of purposes, at several localities, especially Lharidon Bight. The partly lithified coquinite has also been quarried, principally near Boolagoorda and Carbla Point, for use as building stone in the Shark Bay area.

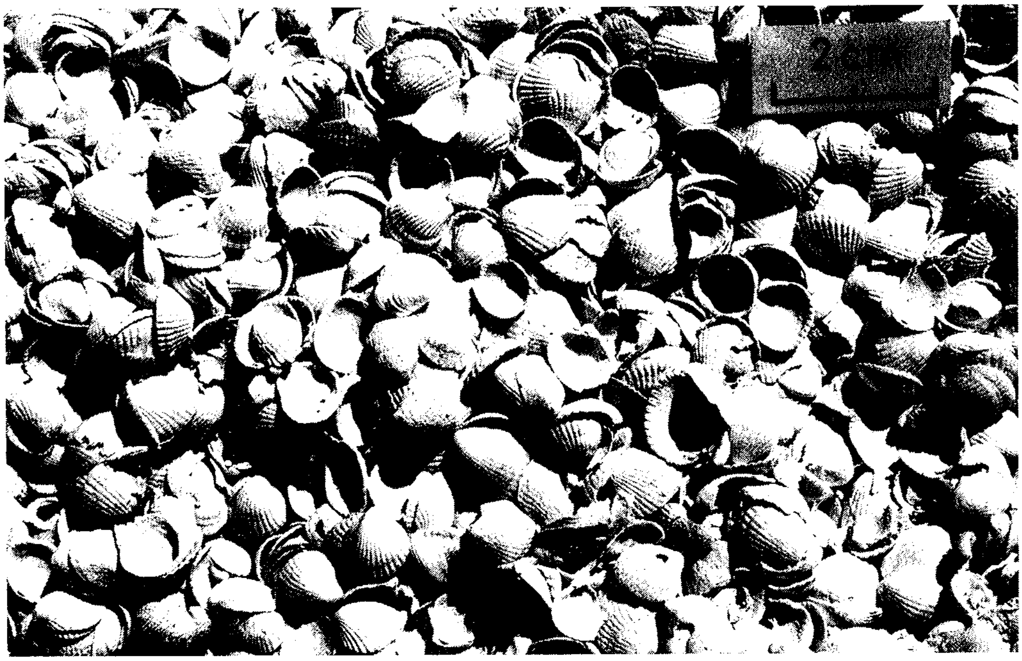

Figure 5. Hamelin Coquina from the modern beach ridge at Carbla Point, showing shells of *Fragum erugatum*.

The oldest (furthest inland) beach ridges must have formed when the waters first became hypersaline following development of the Faure Sill. Preliminary radiocarbon datings by the Geological Survey (yet to be published) suggest that this was about 4,200 years ago, i.e. about 1,800 years after the sea rose to its present level at the end of the Flandrian Transgression.

Stromatolites are the other, and most famous, element of Holocene geology of Hamelin Pool; they are discussed in the following section.

Stromatolites

Introduction

The term stromatolite, as used in this paper, is applied to organosedimentary structures with vertical relief above the substrate, produced by sediment-trapping and/or precipitation resulting from the growth of benthic microbial communities, principally cyanobacteria.

Some authorities restrict the term stromatolite to laminated microbial bodies (e.g. Burne and Moore 1987), and according to their usage many of the Hamelin Pool forms would not be termed stromatolites, as they lack internal lamination in whole or in part. However, I see little advantage in adopting this restricted definition, and believe that the columnar and mound-shaped microbial structures at Hamelin Pool will continue to be known as stromatolites, in accord with common usage of the term among geologists and biologists.

The Hamelin Pool stromatolites have been the subject of a great deal of research, the principal publications being by Logan (1961), Logan, Hoffman, and Gebelein (1974), Playford and Cockbain (1976), Playford (1980a, 1980b), Golubic (1982, 1983, 1985), and Bauld (1984).

Why stromatolites occur at Hamelin Pool

Stromatolites are abundant, in a wide variety of forms, in Hamelin Pool, but are rare elsewhere in the world's oceans. There are two primary reasons why they are able to flourish at Hamelin Pool, both of which are linked to the hypersalinity of the water. Firstly it is clear that grazing animals, especially gastropods, which would consume the stromatolite-building cyanobacteria and microalgae, are very much reduced, and secondly there is a general paucity of thallophytic algae, such as seaweeds, which would otherwise utilize ecological niches now occupied by the stromatolites.

The Hamelin Pool stromatolites are regarded as modern analogues of the fossil stromatolites that occur widely in ancient rocks. Stromatolites are thought to have flourished during the Precambrian because of the lack of animal life and competing plants, but with the rise during the Phanerozoic of grazing and burrowing metazoans and higher marine plants, stromatolites became progressively less common in the world's oceans, until today they have almost disappeared. Thus, the conditions in Hamelin Pool, where most elements of the marine biota cannot survive, mimic conditions in the world's oceans during the early Palaeozoic.

Gross distribution

Stromatolites and associated stratiform cyanobacterial mats (formerly known as "blue-green algal mats") are growing today for some 100 km around Hamelin Pool (Figures 6-10). They cover wide areas of the intertidal zone and adjacent sublittoral platform, extending to water depths of at least 4 m. The stromatolites tend to grow together in linear belts, forming wave-resistant reefs.

Living intertidal forms are commonly backed along the shoreline by older dead stromatolites, which apparently grew when relative sealevel was as much as 1 m higher than today. These older dead forms are exposed above high-tide level, and are being actively eroded. They occur in some areas as a series of stepped terraces, which are best seen on the west shore of Hamelin Pool 4.5 km south of Booldah Well. The oldest stromatolites (from the highest terrace) at this locality have recently been radiocarbon dated as 1,000 to 1,250 years old (A. Chivas, written communication, 1988). Emergence and consequent death of these stromatolites may have resulted from recent uplift of the land in this area, perhaps associated with continued folding of the anticlines beneath the peninsulas (Playford 1980a).

Not all stromatolites in the intertidal zone and on the sublittoral shelf are living; a significant proportion are dead. Some died as a result of being overwhelmed with sediment, such as moving sand megaripples, and have since been uncovered. In many cases such exhumed stromatolites have been recolonized by living microbial mats, so that growth resumes. However, in other cases they have not been revived, even when in areas where conditions seem suitable for continuing growth, and it is not known why this is so.

The first paper to be published on the Hamelin Pool stromatolites claimed that they were restricted to the intertidal zone, and this concept was erroneously extended to the interpretation of ancient stromatolites (Logan 1961; Logan *et al.* 1964). However, subsequent investigations showed that subtidal stromatolites are widespread at Hamelin Pool (Playford and Cockbain 1976; Walter and Bauld 1986). Burne and James (1986) have further suggested that the present-day intertidal forms originated as subtidal stromatolites, which were stranded as a result of a relative fall in sea level. However, although this may be true in some cases, it is clear that many of the existing intertidal forms have grown wholly in the intertidal zone, as evidenced by their internal morphology and degree of cementation.

Stromatolite types

Nine types of microbial mats are recognized at Hamelin Pool, known as colloform, gelatinous, smooth, pincushion, tufted, pustular (mamillate), film, reticulate, and blister mats (Bauld 1984; Golubic 1985; Skyring and Bauld in press). Each of these has a characteristic microbial assemblage of cyanobacteria (one or more species), accompanied by microalgae in some mat types. The different mats occur in zones parallel to the shoreline, controlled primarily by their position within the tidal range.

Three of these mat types build columnar and mound-shaped stromatolites at Hamelin Pool: pustular, smooth, and colloform mats. The others form stratiform microbial mats, with little or no relief above the surface. The depth distribution, main biotic components, and morphology of the three stromatolite types are illustrated on Figure 6.

Pustular mat (mamillate mat of Golubic, 1985) forms small to large columns and mounds, up to 1 m wide and 40 cm high, in the intertidal zone (Figures 7, 8). It may also colonize the tops of smooth mat stromatolites as they grow higher in the intertidal zone. Pustular mat is built by the coccoid cyanobacterium *Entophysalis major*. This organism is thought to be a descendant of the Precambrian stromatolite-building cyanobacterium *Eontophysalis*, and this represents one of the longest-continuing biological lineages known (Golubic 1983).

Smooth mat constructs smaller stromatolite columns and mounds, mainly relatively small, in lower intertidal to shallowest subtidal environments (Figure 10). Smooth mat may also colonize the tops of colloform-mat stromatolites as

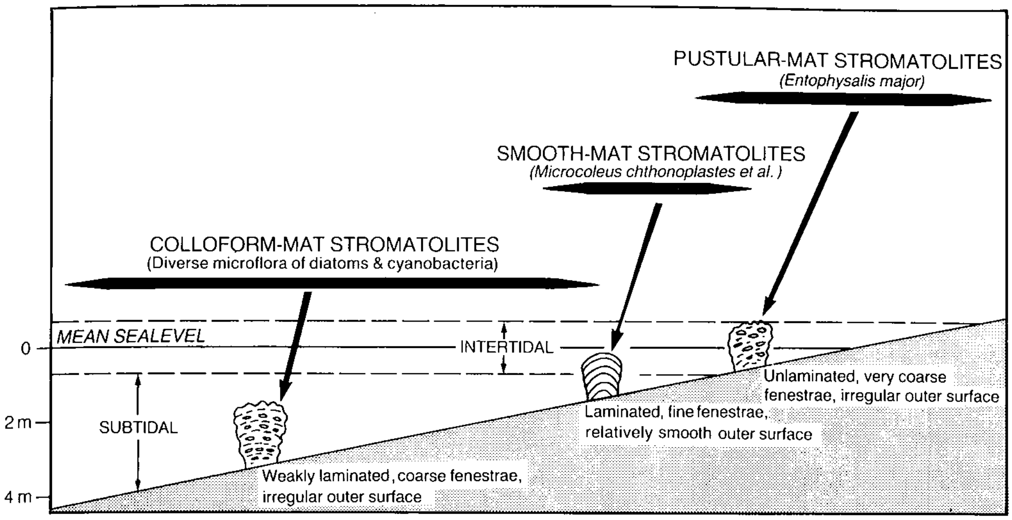

Figure 6. Diagrammatic section illustrating the distribution in relation to sealevel of the Hamelin Pool stromatolites, their microbial mats, and their morphological characteristics.

Figure 7. Club-shaped pustular-mat stromatolites in the intertidal zone at Carbla Point.

Figure 8. Longitudinal pustular-mat stromatolites, elongate parallel to the direction of wave translation, 4 km south of Yaringa Point.

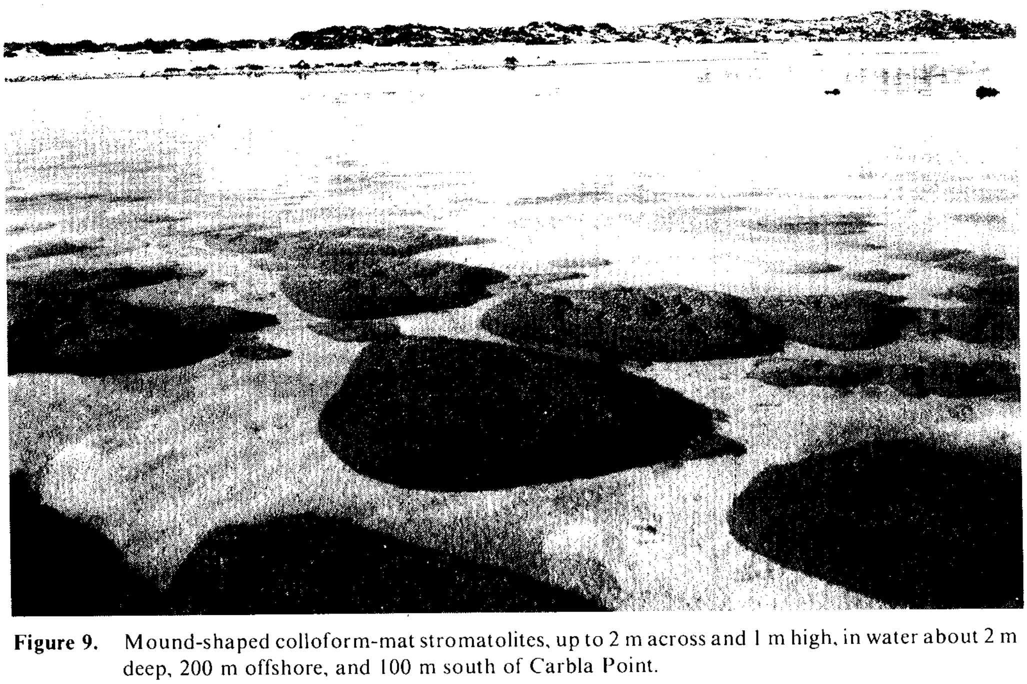

Figure 9. Mound-shaped colloform-mat stromatolites, up to 2 m across and 1 m high, in water about 2 m deep, 200 m offshore, and 100 m south of Carbla Point.

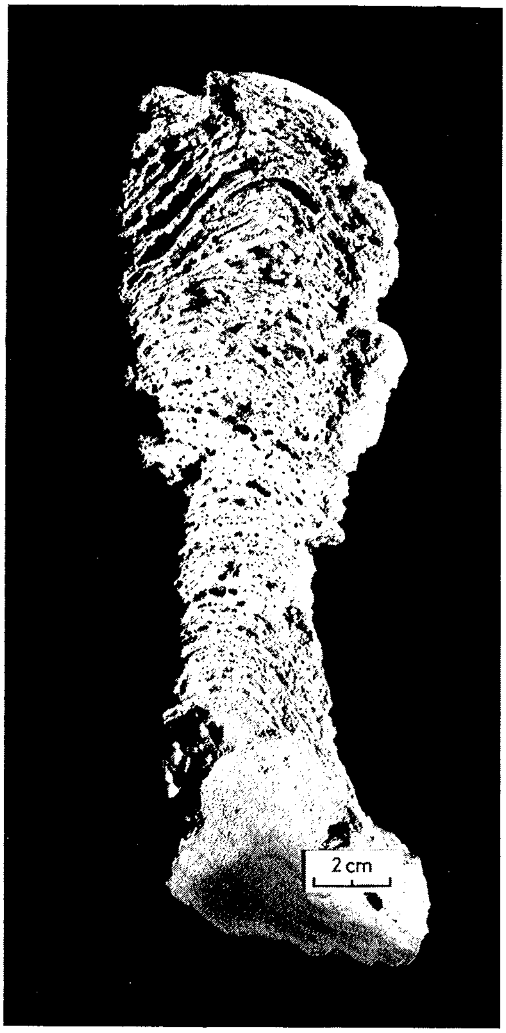

Figure 10. Section through a small smooth-mat stromatolite and the calcrete foundation on which it grew, from Flagpole Landing. Note the relatively well-developed lamination and fenestral void system in the stromatolite, and the pseudo-stromatolitic (inorganic) lamination and bulbous form of the calcrete, which localized growth of the stromatolite.

they grow upwards into the intertidal zone. The principal agent of stromatolite construction is the filamentous cyanobacterium *Microcoleus chthonoplastes*; subdominant filamentous species are the cyanobacterium *Schizothrix* sp. and various flexibacteria (Bauld 1984, Golubic 1985).

Colloform mat forms large stromatolite columns and mounds up to 1 m high and several metres across (Figure 9) growing in subtidal environments, in water depths of up to 4 m (Playford 1980a; Walter and Bauld 1986). The microbial assemblage consists of a very diverse diatom flora and several species of cyanobacteria (J. Bauld, written communication 1989). The diatoms include some stalked forms, whose role in mat construction is at least as important as that of the cyanobacteria (J. Bauld, written comunication 1989). Macroalgae, especially *Acetabularia,* serpulid worms, and various other fauna are commonly attached to lithified surfaces of colloform-mat stromatolites (Bauld 1984; Golubic 1985; Walter and Bauld 1986).

Of the three stromatolite types, colloform-mat stromatolites contain the most diverse microbial flora and associated biota, and this is believed to be because they remain permanently submerged, under relatively constant salinity. The least diverse biota is found in high-intertidal pustular-mat stromatolites, which are exposed and subject to partial desiccation for prolonged periods each year.

Growth rates of stromatolites

The Hamelin Pool stromatolites grow very slowly by a process of accretion, through the trapping and binding of lime-sand and mud particles by a network of filamentous microorganisms, principally cyanobacteria. Some precipitation of calcium carbonate probably also occurs as a result of organic processes, and may play an important role in stromatolite cementation.

The growth rates of living stromatolites have been monitored over a period of 20 years, using non-corrosive nails placed as markers. This method has shown that the stromatolites are extremely slow growing, with maximum growth rates of less than 0.5 mm per year (Playford 1980a). Similar, but more precise, rates have recently been determined by carbon-14 analyses of stromatolites collected at Hamelin Pool, which showed long-term growth rates of about 0.3 mm per year (A. Chivas, written communication 1988). Field experimental data by Bauld and others (1979) have also shown that the highest primary productivity is found in subtidal colloform mat, and the lowest in intertidal smooth mat.

Most living intertidal forms seem to be virtually static, with growth balanced by erosion through wave action. The most active stromatolites are those in subtidal environments, although these are still subject to significant erosion during storms. A single storm may remove the growth of several years. The very slow growth rates indicate that some living stromatolites are probably hundreds, or perhaps even thousands, of years old. It seems possible that the commencement of stromatolite growth began some 4,200 years ago, when Hamelin Pool first became hypersaline.

The extremely slow growth rates of the stromatolites, their fragility, and susceptibility to damage by human activities, are well shown by wheel marks left more than 50 years ago by camel wagons pulled through living stromatolites near Booldah Well (Playford 1980a). These tracks are still so distinct that it would appear to a casual observer that they were made during the last year or two.

Clearly it will be several centuries before the damage at this locality will disappear through regrowth of the stromatolites.

Controls on stromatolite morphology

The morphology of the Hamelin Pool stromatolites is governed partly by environmental factors, and partly by the microbial communities that build them. The relationship between internal fabrics and microbial communities is illustrated on Figure 6. This shows that the best lamination occurs in smooth-mat stromatolites (Figure 10), which also have the smallest fenestrae and smoothest external surfaces. Colloform-mat stromatolites are weakly laminated, with coarse fenestrae and irregular external surfaces, while pustular-mat forms are virtually unlaminated, and have very large fenestrae and irregular outer surfaces.

Further work needs to be done to more closely link details of the internal fabrics of the stromatolites with the microbial communities that build them. There is also a need to examine the processes involved in lithification of the stromatolites, and the extent to which the precipitation of cement is linked to organic versus inorganic processes. Lithification generally begins one or two centimetres below the living mat, but the mechanisms involved are not understood.

The principal environmental controls on stromatolite morphology are the wave-translation and prevailing wind directions, and the nature of the substrate (Playford 1980a).

Stromatolites at Hamelin Pool are commonly elongate in the direction of wave translation (Figure 8), apparently as a result of the scouring action of waves on the living mats. "Leaning" stromatolites near Carbla Point are inclined to the south, towards the prevailing wind, which is thought to have controlled growth in this direction, although the mechanism involved is not clear. Playford (1980a) also invoked wind-induced Langmuir circulation (paired helical vortices) in water to explain "seif" stromatolites on the west side of Hamelin Pool.

The nature of the substrate is a very important control on stromatolite development, as the stromatolites generally require a rocky substrate on which to grow. In various areas this consists of calcretised Cretaceous chalk (Toolonga Calcilutite), Tertiary silicified sandstone (Lamont Sandstone), and calcretised or otherwise lithified Pleistocene beach ridges and marine limestone (Bibra Limestone).

Stromatolites have grown principally around headlands rather than in bays, because the headlands have the required rocky substrate to initiate stromatolite growth. Where there is no rocky substrate, stratiform cyanobacterial mats tend to develop rather than columnar or mound-shaped stromatolites. On the east side of Hamelin Pool, headlands are localized by outcrops of Lamont Sandstone (such as at Carbla Point) or lithified Pleistocene beach ridges; on the west side they are commonly marked by similar lithified Pleistocene beach ridges. Stromatolites growing on such beach ridges occur in characteristic curvilinear belts, controlled by the lines of resistant ridges.

Conclusion

Shark Bay will continue to be an area of major interest to geologists because of its unique sedimentary environments, which include the habitat for the best developments of living stromatolites known from modern seas. Although there has already been considerable research conducted in the area, there is still a great deal remaining to be done, especially in relation to the growth and lithification of stromatolites and the history of Quaternary sealevel and climatic changes in the area.

The Tamala Limestone is a unit of considerable importance in coastal areas of southwestern Australia, but it has yet to be studied in any detail in the Shark Bay area, where the formation reaches its maximum development. The Tamala Limestone was probably laid down during several glacial periods of the Pleistocene, and a careful study of the unit at Shark Bay may provide a basis for its subdivision and for distinguisihing its various phases of deposition.

The relationships between the Tamala Limestone and Peron Sandstone also deserve further study, especially to determine the factors responsible for the accumulation of lime sand dunes on the one hand and siliceous sand dunes on the other. The associated birrida evaporite deposits also warrant research to determine the climatic conditions under which they accumulated.

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